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Physico-Chemical Properties of Agricultural Residues and Strengths of Portland Cement-bound Wood Products

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The physico-chemical characteristics of a few agricultural residues of relevance in the context of their utilization as building materials are presented. Their reaction with alkalis has been studied to ascertain the reason for the poor strength development in portland cement-wood compositions. It is concluded that the poor strength is due to the acidic character of lignocellulosic materials which greatly affects their adhesion with the portland cement hydrate network.

India produces large quantities of agro-industrial wastes[1]. These wastes pose disposal and pollution problems and, therefore, their utilization has assumed considerable importance. Several recent investigations carried out in India and elsewhere[2-8] have shown that some of these wastes could be used for producing a variety of building materials. However, most of these technologies have not been implemented in actual practice for a variety of reasons. Agricultural residues differ from one another largely due to differences in their physical forms and structures and the noncellulosic materials present. Moreover, lignin, which is a binding material in plants, seems to be present mainly on the fibre surface in a more condensed state in some than in others. An understanding of the structures and properties may lead to the development of appropriate technologies for their proper utilization. With this in view, the physical and chemical characteristics of a few agroindustrial residues were studied. The results obtained are presented in this paper. The chemical analyses of the ashes obtained from them are given in Table 1.

Groundnut husk

Groundnut husk, having the shape of an irregular semicircular to semi-cylindrical shell, is quite strong. The upper layer of the husk is soft, glazy and reinforced with a fibrous network. The inner layer has a closely knit cellulosic structure. The bulk density of the husk is 125-150 kg/m^3. It gives an acidic water extract. Compared to other agro-wastes, its lignin content is quite high[9]. Cold and hot water solubles in groundnut husk are 8-9 and 13-15% respectively (Table 2). On calcination, the husk yields 2-5% ash, which has a high percentage of lime and alkali carbonate/oxalate. If kept exposed, the outer layer of the husk is easily destroyed by fungus.

Rice husk

Rice husk has a flat boat-like structure and is quite tough. It is 0.5-1.2 mm in length and 0.15-0.3 mm in breadth and is tapered to a sharp pointed end. It is light yellow in colour. The outside glazed surface is rough, the roughness being unidirectional; the underside is smooth. It is brittle when dry. It gives short fibre (< 1 mm). It is light, with bulk density 100-150 kg/m^3 and specific gravity 750 kg/m^3. It does not easily incinerate due to its high silica content (~ 20% by wt). On calcination, the husk yields 10-22% ash, which contains 90-94% silica, mostly in amorphous form[10]. It easily gets wet with water and the water extract is acidic. The husk is quite durable, but turns black/grey on remaining wet for a long time.

Coconut husk, coir and pith

Coconut husk is elliptical in shape and an average sized husk weighs about 400 g. Its outer cover is a hard glazed skin ~ 1 mm thick. The

Table 1—Chemical Analysis of the Ashes Obtained from Different Agricultural Residues

	SiO_2 %	$R_2O_3(Fe_2O_3 + Al_2O_3)$ %	CaO %	MgO %	Presence or absence of alkali carbonates
Groundnut husk	9.8	27.45	17.64	Traces	Present
Rice husk	94.12	3.75	1.66	—	Absent
Coconut pith	48.2	29.9	17.8	2.76	do
Arhar stick	8.47	22.8	22.03	Traces	Present
Jute stick	21.16	7.43	36.5	3.30	do
Rice straw	94.04	2.20	2.20	Traces	Absent
Wheat straw	58.66	9.52	1.20	1.00	do
Bagasse	83.46	8.00	4.00	3.50	do
Bhabar	52.30	5.50	22.08	5.50	do
Munj	74.50	6.73	14.21	2.26	do
Banana stem fibre	9.87	40.0	12.3	17.3	Present
Coir	50.1	5.20	21.30	14.70	do

Table 2—Chemical and Physical Characteristics on Different Agricultural Residues

	Bulk density kg/m^3	Cold water solubles %	Hot water solubles %	Acid val. of aq. dispersion mgNaOH/g	NaOH reqd when boiled with 5% NaOH soln for 1 hr mg NaOH/g	Cellulose %	Lignin %	Pentosan %	Ash %
Groundnut husk	125-150	4.5-8.0	5.0-11.0	2.52	—	50.6	30.6	11.1	2-5
Rice husk	100-200	1.7-2.0	3.5-4.4	0.94	264	—	—	—	18-22
Coconut pith	80-110	1.5-2.0	3.5-6.0	1.12	460	35.0	25.2	7.5	10.16
Arhar stick	400-500	4-5	6-6.5	1.69	297	—	—	—	—
Jute stick	65-90	0.75-1.0	1.1-1.75	0.44	358	57.6	21.3	18.8	0.3-0.5
Rice straw	150-200	7.5-8.0	10-14	1.79	389	53.5	25.5	21.0	12
Wheat straw	55-80	10-13	14-16.5	1.15	460	51.5	21.5	23.5	15-18
Bagasse	190-200	22-27	25-29.5	1.3	—	43	23	27.5	2-4
Bhabar	25-40	10-23.5	15-33	0.35	160 (Fibre)	53.8	22.2	24.0	4.8-5.0
Munj	40-50	4-6	6-10	0.82	—	58.2	20.5	23.7	2-3
Banana stem fibre	18-150	10-15	12-20	0.61	185	46.7	14	18	10.0
Coir	150-280	3.8-4.1	5.71	1.6	430	44.0	47.6	16.2	1.5

husk of a mature coconut consists of numerous fibres embedded in the pith. The fibres are 15-35 cm in length and their cross-sectional thickness varies from 0.1 to 0.4 mm. The bulk density of the fibre is 150-280 kg/m³ and that of the pith, 80-90 kg/m³. The tensile strength of fibre of 0.20-0.33 mm cross-section is 14-16 kg/cm²; the elongation at break is 10-15%. Water extract of the fibre and pith is acidic. The water solubles content in them is 1.5-6.0%, depending upon the temperature of the water[11]. Lignin, fat and resin contents are more in the fibre than in the pith. On calcination, the pith gives 10-15% ash; the fibre gives 1.5% ash. The ash contains nearly 50% silica. Alkali carbonate and oxalate are also present in the ash. The fibre and the pith obtained on retting are substantially different from those obtained by mechanical decortication. The retted fibre is white, whereas the other one is brown. The pith obtained by retting is dark brown and is comparatively free from water solubles. However, it contains a lot of fine sand and appreciable quantity of sea salts.

Arhar stick (*Cajanus* sp.)

Arhar sticks are obtained on separating the grain from the plant. Arhar plant has a solid woody trunk enveloped with a thin bark-like covering. It has many thin branches and is ~ 3 m in height. The bulk density of arhar sticks is 480-500 kg/m³. On water soaking, it becomes soft and flexible. The water extract of arhar stick is acidic. The stick contains 4-6% water solubles. On burning, 1.5-2% ash is obtained. The sticks are susceptible to fungal attack.

Jute stick *(Corchorus capsularis)*

Jute sticks are the wood residues left after the extraction of bast fibre from the jute plant. It is soft and presents a smooth surface. The girth varies from 2.5 to 7.5 cm at the bottom and from 0.5 to 1.0 cm at the top. It is practically solid at the bottom, but hollow upwards. The sticks are extremely light. The bulk density is 65-90 kg/m³ and the specific gravity, 2.0-2.25. It burns swiftly and yields 0.3-0.5% ash, which is mostly calcium oxide. The contents of cold and hot water solubles are low, but the alkali solubles content is quite high (Table 2). The water extract is acidic. The cellulose content is high[12]. Jute sticks are susceptible to decay on exposure to weather.

Rice straw

The dried stalk and leaves of a rice plant constitute rice straw. It is normally used as livestock feed, and as bedding and packing material. A lot of it is also allowed to decay in the field. A single rice straw is 50-150 cm long and carries 5-6 leaves. The stem has a glazy surface and is hollow in between two nodes. It is pale yellow in colour and is very susceptible to decay when kept wet. The bulk density of rice straw is 200-400 kg/m³. Compared to other agricultural residues, water solubles content in rice straw is quite high (Table 2). These soluble substances possess inhibiting action on the hydration and strength build-up of portland cement. Rice straw on calcination gives 11-14% ash.

Wheat straw

Wheat is a grass-type plant, 45-150 cm in length. The leaves are long and slender. The dry straw is pale yellow to golden brown in colour. The stems are hollow in between two nodes and have a glazy surface. Wheat straw is mostly used as cattle fodder; therefore, it is cut into smaller bits in the thresher itself. The bulk density of the cut wheat straw is 55-80 kg/m³. Its water extract is acidic. Wheat straw develops off-smell if it is kept in contact with water for a day or two. On burning, it gives 18-22% ash. Like rice straw, wheat straw also shows strong inhibiting action on the hydration of portland cement and strength development in it.

Bagasse (*Saccharum officinarum*)

Bagasse is a fibrous residue left after crushing of sugarcane for juice expression. While the upper layer of the cane consists of a hard fibrous substance, the inside is a soft cork-like material, generally called pith. The fibre and pith contents of dry bagasse are about 65 and 35% respectively. The sugar contents in different samples of bagasse show wide variations, depending upon the method adopted for juice expression. Pith is almost a non-fibrous material and has practically no strength. It is highly porous. The water extract of the fibre and pith is acidic. The bulk density of bagasse is about 190 kg/m^3. A sample of bagasse gave the following results on analysis: Cellulose, 42; lignin, 24; and pentosan, 31.3%. On calcination, it gives 2-3.5% ash, which is mostly silica. The bagasse fibre after the removal of the pith is resistant to decay.

Bhabar *(Eulaliopsis binata)*

It is a greenish yellow grass with stalks of 80-120 cm length. Leaf blades are hardly distinct from the sheath. It is also called Sabai grass and is an important raw material for paper making. It grows in U.P., Bihar, Orissa and Punjab. The fibre obtained from bhabar is classified as hard fibre and is used mostly as twine and rope for cots, etc. Its bulk density is 40-60 kg/m^3. On calcination, it gives 4.8-5.0% ash, which consists mostly of silica and lime. The cold and hot water soluble contents vary widely, depending upon the condition of the leaves. A fungus infected leaf has a very high water soluble content. The water extract of bhabar is acidic. The plant yields about 50% fibre, which is fairly resistant to water.

Munja (*Saccharum bingalense* Retz)

Munja is a very large tufted grass. It is not used as fodder for cattle. Its stems are 3-6 m long. The leaves are up to 2 m long. The upper leaf sheaths of the flowering culm yield a valuable fibre, known as *Munj*. The fibre is quite strong and is used for preparing ropes, cordage, etc. It is dirty yellow to creamy yellow in colour. Its alkali solubles content is very high. The cellulose content is also high. On calcination, it yields 2-3% ash. The water extract of the fibre is acidic.

Banana stem fibre *(Musa sepientum* and *M. paradisica)*

The banana plant is not a tree, for it has no woody trunk. In fact, the plant portion above the ground is a false stem. It consists of long leaf stalks wrapped lightly together in a long stiff bundle. The bulk density of the green plant is 700-750 kg/m^3, and that of the dry plant, 50-60 kg/m^3. The stem is fibrous and small quantities of a textile grade fibre are extracted from it. The green plant yields 1-2% fibre, depending upon its size and variety. The bulk density of the fibre is 18-150 kg/m^3. The fibres extracted from the banana stem differ widely in their lengths and diameters. The contents of cold and hot water solubles are 10-18 and 13-25% respectively. The benzene soluble content in a dry banana plant is 0.50-0.75%. The water extract of the fibre is acidic. The dust from a typical banana stem sample gave the following results on analysis: Cellulose, 46.7; lignin, 18.1; and pentosan, 15.9%[13]. On burning, the fibre gave 8-12% ash.

Action of water and alkalis on agricultural residues

Grasses, cereal straw and other annual plants have high pentosan and hemicellulose contents. These are hydrolysed to simple water soluble sugars by the action of mineral acids and they go into solution when treated with dilute alkalis. Water does not react chemically with their wood constituents at room temperature; it only dissolves out the water soluble extraneous substances present in them. The dried forms of almost all agricultural residues give water soluble leachates of varying acidity levels. The fibre acidity varies in wood also. The strength of the solution in contact with the residues remains almost the same even on storage (25-27°C) for a week or more. A slight increase in acidity has, however, been observed in a few cases. The acidity reappears within a few hours after the solution is neutralized with sodium hydroxide solution. The titre value at this stage is more or less the same as the initial value[14]. All agricultural residues attain a certain *p*H when kept immersed in water. On boiling with 5% sodium hydroxide solution for 1 hr, the acid value of various agricultural residues varies from 260 to 475 mg NaOH/g (Table 2).

While discussing the theory of alkali delignification of wood, Emil *et al.*[15] pointed out that sodium hydroxide is first absorbed by acidic hydroxyl groups on the lignin, and then as the temperature rises, a chemical combination between lignin and the absorbed alkali takes place; finally alkaline hydrolysis of the assumed lignin-carbohydrate bond occurs. In the meantime, hemicelluloses and polysaccharides dissolve and consume some of the alkali. The process appears to continue slowly till the entire quantity of hemicelluloses and lignin has reacted with the alkali. In fact, dilute alkaline solutions seem to dissolve only some hemicelluloses and have a slight degrading effect on lignin, especially when the solution is cold.

Portland cement bound wood products

The above observations assume considerable importance in explaining why cement bound wood products are weak as compared to cement bound asbestos and silica products. There can be three main reasons for the poor strength of cement-bound wood products: (i) unlike asbestos, they lack self-dispersing capacity and buoyancy in aqueous medium; (ii) the absence of chemical affinity with them for cement; and (iii) acidic character of their water extract. Like lignocellulosic substances, sand produces an acidic aqueous solution. However, its acidity does not appear for a long time after it is once neutralized. The aqueous dispersion of asbestos is alkaline. Under these conditions, a chemical bond between calcium silicate hydrate and asbestos or sand can be visualized, whereas it is unlikely that an interfacial surface between wood and calcium silicate hydrate is ever homogeneous. With continuing dissolution of lignin and polysaccharide and salt formation, the alkalinity generated as a result of hydration of cement grains is neutralized. The aqueous dispersion of cement grain is alkaline, the interfacial surface of wood and the hydrated products of cement is neutral and that of wood particle is feebly acidic. Under these conditions, the chances of the formation of a chemical bond become very remote. Therefore, it results in poor strength of portland cement bound lignocellulosic products.

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